CHEMICAL ENGINEERING TRANSACTIONS

VOL. 59, 2017

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Zhuo Yang, Junjie Ba, Jing Pan

ISBN 978-88-95608- 49-5; **ISSN** 2283-9216

DOI: 10.3303/CET1759182

Chemical Emergency Supply Chain Risk Evaluation and Mitigation for Major Natural Disasters

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The operation of the chemical emergency supply chain may be destroyed by the risk events, such as major natural disasters and other emergencies, which can bring about the decreasing of node operating capacity. Since the relationship among the nodes, the risk of a node will be transferred between nodes, and finally spread to the entire chemical emergency supply chain. This paper establishes and analyses the risk assessment model of chemical emergency supply chain, and then taking some certain chemical emergency supply chain as an example, analyses the risk results of the chemical emergency supply chain under risk accidents, and presents the risk mitigation strategies.

1. Introduction

Taking the time efficiency as the core goal, the chemical emergency supply chain is a dynamic supply chain alliance formed by the government which provides technical and financial support and composed of several suppliers which are the foundation of emergency rescue. In recent years, the research on chemical emergency supply chain risk has been concerned by a growing number of scholars. Whether it is theoretical research or practical application, some achievements (Zhi and Min, 2015; Cannistraro et al., 2016) have been made, mainly in the following aspects: The major objective of the supply chain risk management is to achieve the risk evaluation, risk mitigation and risk monitoring (Kang and Kim, 2012). As a significant step in risk management, risk evaluation is the elementary method to measure risk and the foundation to mitigate risk (Ruiz-Torres and Mahmoodi, 2007; Chen et al., 2016). Risk evaluation methods mainly consist of fuzzy comprehensive evaluation method, the grey estimate model (Xanthopoulos et al., 2012), Conditional Value at Risk (CVaR), mean-variance method and the Inoperability Input-output Model (IIM) method (Haimes and Jiang, 2001). Major natural disasters have adverse effects on chemical emergency supply chain, which need to be mitigated by effective means.

There have been abundant methods and models for risk assessment mitigation in chemical emergency supply chain, but it should be noted that there is a lack of a combination of qualitative and quantitative methods (Ou et al., 2004). Most of the achievements research problems about risk evaluation and mitigation mechanism from a qualitative perspective, and are less concerned about the relationship among the nodes and the impact chemical emergency supply chain. In this paper, the chemical emergency supply chain risk evaluation model has been established based on IIM and the operational result and risk mitigation strategy in chemical emergency supply chain has been analysed, which is descripted in the following sections.

2. Chemical emergency supply chain risk analysis

2.1 Definition of chemical emergency supply chain risk

In this paper, the chemical emergency supply chain risk of which value is range 0 from 1 is defined as the non-operational risk of the node in chemical emergency supply chain. When the value is 0, it indicates that the actual performance of the node is exactly the same as the planned performance. When the value is 1, the actual performance and the planned performance of the node are completely inconsistent, which means the subsystem of the node is completely collapsed. Chemical emergency supply chain risk includes internal and external risk. External risk mainly involves natural environment, economic environment, political environment and cultural environment uncertainty. The internal risk comprises the risk of supply and demand and emergency internal operation risk. According to the definition, the non-operational risk can reflect the decreased capacity of the node in chemical emergency supply chain, and the safeguard quantity of the node in chemical emergency supply chain can be reflected by the total tonnage that the individual node can support within a certain period of time. So the non-operational risk is closely related to the losses of safeguard quantity. In (Wei et al., 2010), the research considers that there is a linear relationship between the non-operational risk and the losses of safeguard quantity. Through the chemical emergency supply chain risk evaluation model, we can calculate the non- operational risk value of the chemical emergency supply chain under the event of major natural disasters.

2.2 Problem description

As the external risk of chemical emergency supply chain is more uncertain and destructive than the internal risk, this paper discusses the external risk for major natural disasters. The research object is a chemical emergency supply chain system which contains second level supplier, first level supplier, government material acquisition centre, material distribution centre and rescue demand. The nodes which shape the basis of the whole material support are closely linked and interrelated. The chemical emergency supply chain is facilely affected by the event of major natural disasters, which will transmit the risk to the whole nodes and result in the losses of safeguard quantity. Consequently, it is the core of this paper to calculate the value of non-operational risk and the losses of safeguard quantity in chemical emergency supply chain.

2.3 Model presumption

This paper proposes the following presumptions:
1) The chemical emergency supply chain risk analysis is within a certain range of time; 2) During this time-frame, the topological structure of chemical emergency supply chain remains stabilized; 3) There is a linear relationship between the non-operational risk and the losses of safeguard quantity; 4) The supply of upstream nodes can meet the demand of downstream nodes, which means there is no shortage.

3. Modeling

3.1 Illustration of symbols

q_i: j=1, 2, …, n: total non-operational risk of node j;
p_{ij}: I, j=1, 2, …, n: the non-operational risk of the node i which is caused by the node j;
b_{ij}: I, j=1, 2, …, n: the non-operational risk probability of node i caused by node j;
c_i: i=1, 2, …, n: direct non-operational risk of node I;
$c=[c_1, c_2, …, c_n]^T$: column vector of direct non-operational risk;

$W=(w_1, w_2, …, w_n)^T$: weights of OWA based on trigonometric function $\sum_{j=1}^{n} w_j$ =1, $w_j \in [0,1]$, j=1, 2, …, n;

u_1, u_2, u_3, u_4: the most important factors affecting the interdependency among nodes; $Y_i=(y_{lk})_{m\times4}$: evaluation matrix of node I; $R=(r_{lk})_{5\times4}$: standardized matrix; r_{lk}: element in standardized evaluation matrix; b_k: the value of k in r_l; $V=(v_{lk})_{m\times4}$: the matrix rearranged according to the order from large to small in the normalized matrix R; v_l: for each r_l, the vector is rearranged by order from large to small; a_{il}: the interdependency coefficient of the node i and the node g, h, j, k, p; g: the node g which provides the same products for the node i and j; l_i: the node i maximum demand for the node g without the demand competition of j; S_i: the planned demand of the node i that requests material from j; a_{ij}: the interdependency coefficient and the competitive relationship coefficient; $A=(a_{ij})_{n\times n}$: the matrix which is composed of the interdependency coefficient and the competitive relationship coefficient; Q_i*: the safeguard quantity that the node i can support during a certain time-frame; $\triangle Q_i$: the losses of safeguard quantity of the node I; S: the losses of safeguard quantity of the whole chemical emergency supply chain.

3.2 Modeling

In this paper, IIM is applied to the chemical emergency supply chain risk analysis for the first time. The chemical emergency supply chain is regarded as a complex relationship system composed of nodes from the perspective of system engineering. The disturbance caused by the major nature disasters is regarded as the input of the system, and the non-operational risk is considered as the output of this system, as shown in Figure 1.

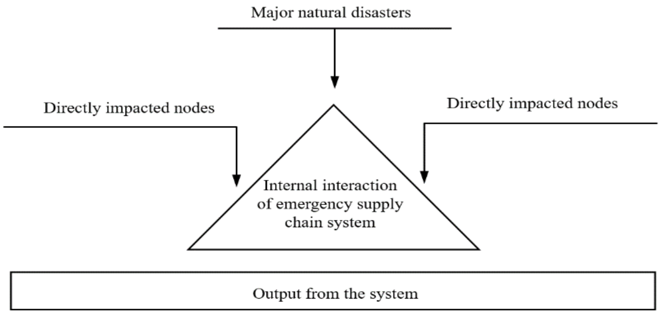

Figure 1: IIM sketch map of chemical emergency supply chain

Figure 1 illustrates the framework for the non-operational risk transmission in chemical emergency supply chain. As to the problem of how the risk transfers through the interdependency among nodes, it is indispensable to propose the non-operational risk transmission mechanism. According to the illustration of the above symbols, we can easily acquire the non-operational risk which is p_{ij} caused by the node *j* is equal to the product of b_{ij} and q_j. Since the total non-operational risk is the sum of the direct risk and the sum of the indirect non-operational risk caused by other nodes in the chemical emergency supply chain. Therefore, the total non-operational risk of the node *i* is:

$$q_i = \sum_{j=1}^{n} p_{ij} + c_i \text{ ,i,j=1,2,…,n} \tag{1}$$

Based on the above mentioned chemical emergency supply chain modeling framework and risk transmission mechanism, the IIM is applied to the non-operational risk analysis of chemical emergency supply chain. The equation is:

$$q = Aq + c \tag{2}$$

If $(I\text{-}A)^{-1}$ exists, the solution of equation (2) is :

$$q = (I - A)^{-1} c \tag{3}$$

3.3 Solution design

After constructing the IIM framework of chemical emergency supply chain, how to obtain the interdependency coefficient and the competitive relationship coefficient matrix $A=(a_{ij})_{n\times n}$ is the key problem to solve the equation (2). In this paper, the interdependency coefficient matrix of chemical emergency supply chain is calculated by modified OWA operator. Now let *F* be the function： $I^n \rightarrow I$(*I* is a set of real numbers); (a_1,a_2 ,…, a_n) is a given vector; the weight vector $W=(w_1,w_2,…,w_n)^T$ is related to the function *F* of which conditions are the arbitrary weight $w_i \in$ (0,1)and the sum of weights $\sum_i w_i=1$. b_i indicates the value of *i* in (a_1, a_2 ,…,a_n). If the following equation is hold:

$$F(a_1, a_2, \ldots, a_n) = \sum_{j=1}^{n} w_j b_j \tag{4}$$

The function *F* is an ordered weighted averaging operator, in which the weight w_i is location-independent, and the w is also called the position vector. According to the characteristics and structure of chemical emergency supply chain, and the opinions of 6 emergency response experts, this paper assumes that the nodes of the supply or demand, reaction rate, reserves level, strategic importance as the master factors affecting the interdependency among chemical emergency supply chain nodes, and replaces those four elements with symbol U_1, U_2, U_3, U_4,, The reaction speed indicates the arrival time of the first rescue material when the support task is carried out. The specific procedure for obtaining $A=(a_{ij})_{n\times n}$ based on the modified OWA operator is as follows:

Step 1: Determined the evaluation matrix of each node separately. Taking *i* as an example to calculate the interdependency coefficient, this design establishes the node *i* which is directly connected to the node (*g*, *h*, *j*, *k*, *p*) and ascertains the authentic value of the quantitative factors in the matrix such as supply/demand and reaction rate. The seven levels of classification criteria are used to evaluate the qualitative factors which are reserves level and strategic importance.

Step 2: Standardize evaluation matrix. The standardized method can be divided into the standard equation:

$$r_{lk} = \frac{y_{lk}}{\sum_{l} y_{lk}}, l \in \boldsymbol{N} \tag{5}$$

$$r_{lk} = \frac{\frac{1}{y_{lk}}}{\sum_{l} \frac{1}{y_{lk}}}, \quad l \in \boldsymbol{N} \tag{6}$$

If the factor evaluation value is larger, it reflects the closer relationship among nodes which are normalized by equation (5) such as supply/demand, reserve level and strategic importance. Instead, equation (6) is applied to standardize the factor that is reaction rate.

Step 3: Calculate the interdependency coefficient. According to the modified OWA operator, the $V=(v_{lk})_{5\times4}$ is obtained by arraying r_l in the $R=(r_{lk})_{5\times4}$ in descending order. At this time the interdependency coefficient is:

$$a_{il} = \mathbf{v}_l \mathbf{W} \tag{7}$$

$W=(w_1, w_2, \ldots, w_n)^T$ is the weights of OWA based on trigonometric function and developed from v_l. The calculation equation of w is as follows:

$$w_j = \frac{\cos \frac{2j-n-1}{2(n+1)}\pi}{\sum_{i=1}^{n} \cos \frac{2i-n-1}{2(n+1)}\pi}, \ j=1, 2, \ldots, n \tag{8}$$

Step 4: Measure the competitive relationship coefficient. Obtaining the coefficient needs the historical data of those relevant organization. The formula is as follows:

$$a_{ij} = \frac{I_i - s_i}{s_i} \tag{9}$$

Step 5: Comprehensive evaluation. The interdependency coefficient and the competitive relationship coefficient of the other nodes in the chemical emergency supply chain can be acquired by repeating steps 1~5, which can develop the matrix A by means of combining the two coefficients of the whole nodes. The non-operational risk value of the nodes in the chemical emergency supply chain can be calculated by the formula (3).

Step 6: Estimate the losses of safeguard quantity. Due to the linear relationship between the non-operational risk and the losses of safeguard quantity in the model hypothesis, the estimating formula of the losses of safeguard quantity is as follows:

$$S = \sum_{i=1}^{n} \Delta Q_i = \sum_{i=1}^{n} q_i Q_i^* \tag{10}$$

4. Case calculation and analysis

4.1 Case introduction

Taking a chemical emergency supply chain as the example, this paper depends on the chemical emergency supply chain to actualize the support of material A, as shown in Figure 2. With the core node 7 which is considered as government material acquisition centre, the chemical emergency supply chain contains three first level suppliers, three second level suppliers, two material distribution centres and four rescue demands. The node 6 provides packaging material for node 7. Three second level suppliers offer raw material to the node 4 and node 5, and there is a competitive relationship between the two nodes. Provided that there is a major natural disaster disturbing the node 6 directly, which brings about the destruction of warehouses, the risk accident causes the node 6 to decrease the supply of materials to the node 7 by about 40%. Based on the risk evaluation model proposed in this paper, the analysis of the losses of safeguard quantity and non-operational risk of the chemical emergency supply chain nodes is as follows Figure 2.

Step 1: Determined the evaluation matrix of each node separately. The value of the quantitative factor is obtained by the real situation, and the value of the qualitative factor is calculated by the emergency experts according to the actual circumstance of the chemical emergency supply chain, as shown in table 1.
Step 2: Standardize evaluation matrix. The equation (5) is applied to standardize the in the evaluation matrix.
Step 3: Calculate the interdependency coefficient. The $V=(v_{lk})_{5\times4}$ is obtained by arraying r_l in the $R=(r_{lk})_{5\times4}$ in descending order. The equation 7 and 8 can be used to obtain the interdependency coefficient between the node 7 and its connected nodes: $(a_{74}, a_{75}, a_{76}, a_{77}, a_{78}, a_{79})$=(0.111, 0.235, 0.140, 0.241, 0.268).
Step 4: Measure the competitive relationship coefficient. In the chemical emergency supply chain, no more than the node 4 and 5 have a competitive relationship. In a certain period of time, the node 7 requires the node 4 to provide 220 tons of safeguard quantity. According to the historical data of the node 4 and 5, the demand of the node 7 for the node 4 is 360 tons without competition of the node 5. This paper uses the formula (9) to obtain the competitive relationship coefficient: $a_{45}=(l_4-s_4)/s_4$=360-220/220=0.636.
Step 5: Comprehensive evaluation. Through repeating steps 1~5, the matrix A which consists of the interdependency coefficient and the competitive relationship coefficient of the whole chemical emergency supply chain can be acquired.
Step 6: Estimate the losses of safeguard quantity. The non-operational risk of each node can be obtained by the equation (3) of which c=(0, 0, 0, 0, 0,0.400, 0, 0, 0, 0, 0, 0, 0), and the solution of the equation is$(q_1,q_2,q_3,q_4,q_5,q_6,q_7,q_8,q_9,q_{10},q_{11},q_{12},q_{13})^T$=(0.005,0.172,0.005,0.014,0.054,0.496,0.141,0.135,0.091,0.08,0.082,0.043,0.054)^T. Based on the analysis of the topological structure and characteristics of the chemical emergency supply chain, this paper assumes that the safeguard quantity of each node is: (800, 1 500, 950, 850, 980, 750, 4600, 800, 650, 1 380, 1 200, 1380, 1250). Thus, the losses of safeguard quantity are reduced to (4,258,5,12,53,372,649,108,59,110,98,59,68). According to the equation (10), the losses of safeguard quantity of the chemical emergency supply chain can be reduced to: *S=1855*.

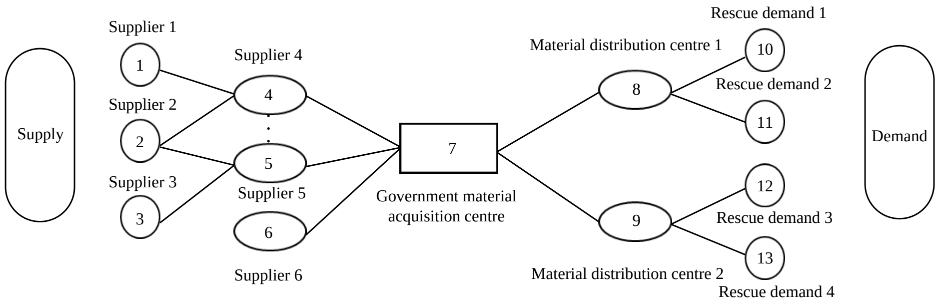

Figure 2: Structure model of Chemical emergency supply chain

Table 1: Evaluation matrix Y_7

Node 7	u1	u2	u3	u4
x4	220	7	3	3
x5	600	4	6	6
x6	140	5	5	4
x8	380	3	7	7
x9	460	2	7	6

4.2 Result and analysis

The non-operational risk and the losses of safeguard quantity of each node in the chemical emergency supply chain is analyzed. In the procedure of applying the risk evaluation model to estimate the risk, it is necessary to conduct a multiple-index evaluation which can catch sight of important nodes in the chemical emergency supply chain. The multi-index evaluation method that considers the indexes of non-operational risk and losses of safeguard quantity is utilized to determine the importance of each node in the chemical emergency supply chain. When the evaluation index is non- operational risk, the node 6 is the most damaged, followed by nodes 2, 7, and 8; When the evaluation index is the losses of safeguard quantity, the node 7 is the most affected, followed by nodes 6, 2, and 8. If the importance of nodes is evaluated from a single index, it is difficult to obtain the optimal solution of chemical emergency supply chain risk management. Based on the above analysis, it can be concluded that node 6 and node 7 are most affected in the whole chemical emergency supply chain. This indicates that the national emergency management agencies should focus on the risk management for the government material acquisition Centre and the first level suppliers when the major natural disaster happens.

4.3 Risk Mitigation strategy

According to the above risk analysis, this paper uses the strategy of increasing the number of first level suppliers to mitigate the risk. Assuming another first level supplier (node 14) provides rescue material for node 7 and shares the half of rescue material of the node 6, the risk evaluation model is applied to validate this risk mitigation strategy. The operational results of non-operational risk and losses of safeguard quantity are shown in table 2. After the risk mitigation strategy, the reliability and robustness of the chemical emergency supply chain are significantly enhanced.

Table 2: The operational results in chemical emergency supply chain after the risk mitigation

Node	1	2	3	4	5	6	7
Non-operational risk	0.001	0.005	0.001	0.003	0.017	0.481	0.066
Safeguard quantity	800	1500	950	850	980	375	4600
Losses of safeguard quantity	1	7	1	2	16	180	304
Node	8	9	10	11	12	13	14
Non-operational risk	0.037	0.032	0.022	0.022	0.015	0.019	-0.150
Safeguard quantity	800	650	1380	1200	1380	1250	375
Losses of safeguard quantity	29	21	30	27	20	24	-56

5. Conclusions

Risk evaluation and mitigation play an important role in both traditional and chemical emergency supply chain risk management. Effective risk mitigation strategy can reduce the risk level of chemical emergency supply chain and improve the security of chemical emergency supply chain. Based on the IIM and the modified OWA operator, this paper establishes the risk evaluation model of the chemical emergency supply chain and obtains the non-operational risk and the losses of safeguard quantity of the chemical emergency supply chain as well as risk mitigation Strategy. The analysis shows that the risk evaluation model can availably mitigate the risk of chemical emergency supply chain, which is a successful reference for emergency logistics and chemical emergency supply chain management. However, in the aspect of logistics modulus, it is necessary to make further research and discussion on the non-operational risk.

Acknowledgments

Financial support for this work is provided by the Academic Innovation Fund of Logistical Engineering University (201103), The China society of logistics, China Federation of Logistics & Purchasing Project Planning (2016CSLKT3-099) and (2017CSLKT3-105), The Innovative Special Funding Project of Logistical Engineering University (201705).

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